Port Injection of Hydrogen Gas in Direct Injection Diesel Engine using DEE as Ignition Enhancer

G. Mohan Kumar, C. Dhanasekaran

Abstract— **Over the past two decades considerable effort has been taken to develop and introduce new alternate source of energy for the conventional gasoline and diesel. Environmental pollution and uncertainty in cost of petroleum products are the principal driving forces for this movement. The major pollutants from an Diesel engine system are NO_x, Smoke, particulate matter, Soot. Several alternative fuels were tried but all of them are carbon based fuels, therefore net carbon based pollutants cannot be reduced. One alternative to carbon-based fuels is hydrogen. Hydrogen a non-carbon fuel only can meet zero emission vehicles standards in future. Hydrogen can be commercially used as a fuel even though it is having a number of technical and economical barriers. Numerous techniques are available for use in C.I. engine such as dual fuel made, by using spark plug, glow plug, DEE as an ignition enhancer. Hydrogen was used in a diesel engine in the dual fuel mode-using diesel as an ignition source in neat form using DEE. In neat form the DEE was introduced in the manifold. In order to have a precise control of hydrogen flow and to avoid the backfire and pre – ignition problems hydrogen was injection in to intake manifold; DEE injection follows the hydrogen injection. DEE mixed with air and flows into the combustion chamber as DEE auto ignites first followed by hydrogen combustion. A single cylinder-four stroke water-cooled naturally aspirated constant speed D.I. diesel engine with a rated output of 3.7 kW at 1500 rpm was used for the experimental purpose. Measurements were taken with respect to the performance, combustion and emission studies.**

Index Terms— **Hydrogen, Injection Timing, Injection Duration, Performance, Emission, Emanation.**

I. INTRODUCTION

In recent days, the significance of environment and energy is more accentuated because, among various energy sources, the fuels for automotive use are drawing attention as they are directly associated with our day to day life. The fossil fuels, which are widely used nowadays, have some grave problems such as restriction over preservation,. unfeasible for recycling and it also produces various kinds of toxic waste emanation[12]. Therefore, various researches were carried on alternative fuels to substitute the fossil fuels Among them, hydrogen has the outstanding advantages of wide flammable assortment and will also not produce unburned hydrocarbon and carbon monoxide[1-4], if there are no lubricants in the combustion chamber. In order to adopt, gaseous hydrogen as a fuel for an internal combustion engine, lots of research were carried out on hydrogen supply system[2,13,14,10], combustion characteristics[5-6] and so on. And many areas of research are concerned with the adoption of in-cylinder type injection system for high pressure hydrogen. This type of injection system can eliminate the possibility of backflow of hydrogen into the intake pipe and can as well produce more power than an intake port injection system. But this system has a very complicated structure and greater durability problem. To overcome the disadvantages of high pressure in cylinder, injection system was tried with timed injection[11]. In this study, an intake port injection system was constructed and installed on a single cylinder engine, using a solenoid as the driving source of the injection valve. In order to minimize the possibility of flashback occurrence, injection timing of the hydrogen injection valve was set within the duration of intake valve opening[7]. Specifically, the hydrogen is supplied while the intake valve is open. So that the hydrogen injected into the intake port could be inducted into the combustion chamber as much as possible[8-9]. With this system, performance and emission characteristics of hydrogen combustion in the internal combustion engine were investigated.

II. EXPERIMENTAL SETUP

The engine used for the experimental investigation was a Kirloskar AV1, single cylinder, four strokes, cooled water, direct injection diesel engine, developing a rated power of 3.7 kW at a rated speed of 1500 rpm.. The engine is coupled to an electrical dynamometer with resistance loading. The engine is mounted on an engine test bed with suitable connections for lubrication and for the supply of cool water. The electronic control unit (ECU) controls the operation of H_2 fuel injector. The one end of the positive power supply from the 12 V battery is connected to the injector; the other negative terminal of the injector is connected to the ECU, which is having the control of injector opening timing and duration. The electronic control unit is also having the input from the infrared detector. The IR Detector is used to give the signal to the ECU for the injector opening timing. The negative terminal of the

This work was supported by the All India Council for Technical Education, New Delhi, under Grant 8023/RID/RPS/11/12/698 Port injection of hydrogen gas in direct injection diesel engine using DEE as ignition enhancer. A. G Mohankumar, B. C Dhanasekaran

G Mohan Kumar is with Park College of Engineering and Technology, Kaniyur, Coimbatore – 641659, Tamilnadu, India (0091-9443743348; gmohankumar68@gmail.com)

C Dhanasekaran is with School of Engineering, Vels University, Pallavaram, Chennai – 600117 (dhans.se@velsuniv.ac.in)

injector is connected to the ECU. Based on the preset timing, the duration the injector will be opened for injection and closed after injection. The injection timing and injection duration will vary within the specified range by using the knob control. The power supply for the injector opening is 4A and for holding the injector to inject the fuel 1A will be the power supply required. Based on the presetting, the hydrogen will flow and the flow of hydrogen can be controlled either by using the pressure regulator or by using the digital mass flow controller. DEE injector is fixed in the intake manifold for DEE injection and the electronic fuel pump was fixed for the purpose of DEE supply. Hydrogen is used in a diesel engine in the dual fuel mode and in neat form using DEE. In neat form DEE is injected into the intake manifold. In order to have a precise control of hydrogen flow and to avoid the backfire and pre-ignition problems, hydrogen is injected into the intake manifold; DEE injection follows hydrogen injection. DEE mixes with air and flows into the combustion chamber and DEE auto ignites first followed by hydrogen combustion. Rota-meter is used to maintain the water flow, at the outlet of the engine. The range of the rota meter varies from 0 to 1000 lpm. Fig. 1 shows the experimental setup.

III. EXPERIMENTAL PROCEDURE

Hydrogen gas is stored on a high-pressure cylinder, which is at 150 bars, is reduced to a value of 3 – 4 bar by using a pressure regulator. Hydrogen is then passed through a fine control valve to adjust the flow rate of hydrogen. Then hydrogen is allowed to pass through mass flow controller, which meters the flow of hydrogen in terms of Standard Litres per Minute (SLPM). Hydrogen is then passed through flame arrestor which is used to restrain possible fire hazards in the system. These flame arrestors operate on the basic principle on which the flame gets douse, if sufficient heat can be removed from the gas by the arrestors. It also acts as a non-return valve. Then hydrogen is allowed to pass through flame trap, which is used to suppress the flash back, if any, into the intake manifold. The flame trap used here is a wet type flame trap. In general, wet flashback arrestor work by turning out the gas into bubbles, in the non-flammable and ideally non-gas-absorbing liquid; and in this case, the liquid used is water. The hydrogen from the cylinder after passing through the flame trap is inducted into the gas injector, which is fitted in the inlet port. The engine was started with diesel as the fuel. Then hydrogen was introduced in the intake port by using hydrogen gas injectors and it is brought to steady state conditions. The engine parameters were measured with different timing. At the end of the process, hydrogen flow rate was reduced to zero and the engine was made to run at steady state condition using diesel at no load condition. The start of injection hydrogen is fixed at TDC and three injection durations of 30° [3.3 ms], 60° [6.6 ms] and 90° [9.9 ms] Crank angles were selected, since the fuel injector can be open for a maximum duration of 10 ms. Experiments were conducted on neat hydrogen using DEE as an ignition source for the combustion of hydrogen in port injection. The performance, emissions and combustion characteristics of hydrogen-DEE operated engine is studied. Hydrogen quantity and the DEE are determined based on the stable operation of the engine. Hydrogen quantity is increased until the engine attains the rated speed and DEE quantity is increased until stable combustion is attained. The

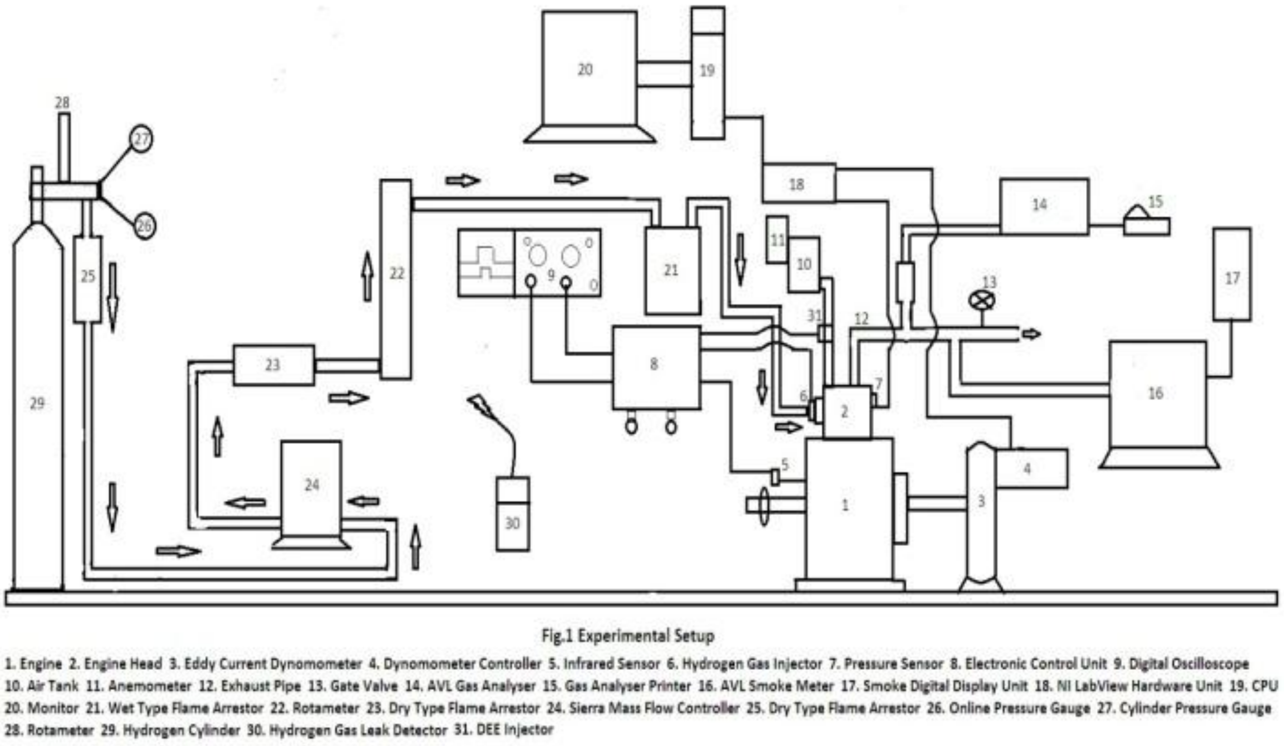

Fig. 1 The Experimental Setup

DEE injector is located on the intake manifold at a distance of 60 mm ahead of the hydrogen port injector. The injection timing of DEE is kept constant as 30° ATDC such that DEE injection starts after the injection of hydrogen (Hydrogen injection starts at 5° BTDC and ends at 25° ATDC) which will prevent the mixing of hydrogen and DEE which in turn avoid any back fire in the intake manifold. An electronic control unit controls the DEE injection duration and flow is regulated by the needle valve regulator assembly. Table 1 shows the energy requirement of DEE to hydrogen at different loads in port injection. Beyond 75 % load, the hydrogen DEE operated engine is not able to attain the rated speed. This is due to increase in hydrogen flow beyond a limit results in more replacement of air hence richening the air fuel mixture. By controlling the hydrogen flow and increasing the DEE flow the engine is not able to deliver the rated power at full load due to high onset of knock, unstable combustion and greater fluctuations in engine speed.

Table 1 Energy requirement of DEE to hydrogen at different loads

Load, %	Hydrogen energy, %	DEE energy, %
0 %	47.59	52.41
25 %	59.67	40.33
50 %	61.58	38.42
75 %	67.77	32.23
Full load	Unstable operation and severe knocking is noticed	

IV. RESULTS AND DISCUSSION

A. Brake Thermal Efficiency

The variation of brake thermal efficiency with load is depicted in Figure 2. It is observed that with DEE operation the brake thermal efficiency of the engine increases. At 25 % load the brake thermal efficiency of hydrogen-DEE operated engine is 17.9 % compared to diesel of 11.9 % and 15.6 % for hydrogen diesel operated engine. At 75 % load the brake thermal efficiency is observed to be 29.3 % for hydrogen-DEE and 26.23 % for hydrogen diesel dual fuel engine whereas for diesel it is observed to be 21.59 %. The increase in brake thermal efficiency is due to higher latent heat of vaporization of DEE that makes the inlet charge to cool by about 12-15 °C. As the inlet charge cools, the inlet charge (both hydrogen and air) density increases, which in turn results in better combustion hence an improvement in brake thermal efficiency is noticed.

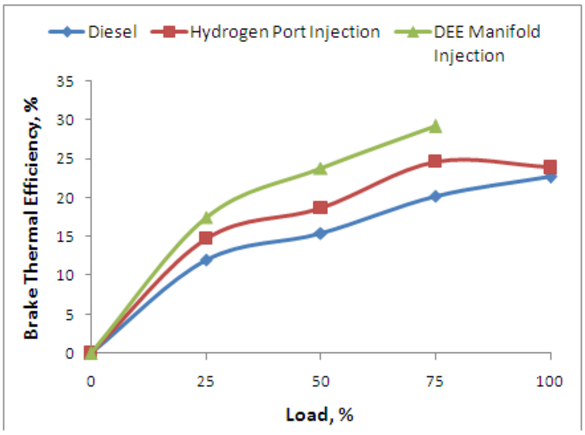

Fig. 2 Effect of Brake Thermal Efficiency with all Load Conditions

B. Specific Energy Consumption

Figure 3 depicts the variation of SEC with load. In general the SEC of DEE-hydrogen operated engine is lower compared to hydrogen-diesel dual fuel engine. At 50 % load the SEC is 4.11 in the DEE operated hydrogen fuel engine compared to 4.66 in the case of hydrogen diesel dual fuel engine and diesel of 5.93. The SEC at 75 % load in the hydrogen-DEE operated engine is 3.41 compared to diesel of 4.63 and 3.81 in hydrogen diesel port fuel operation. The reduction in SEC is due to the lesser replacement of air by hydrogen. A reduction in SEC for hydrogen-DEE engine compared to that of hydrogen-diesel dual fuel engine can also be noticed due to lesser replacement of air in hydrogen-DEE engine as a result of reduction in inlet charge temperature by DEE by about 10° C.

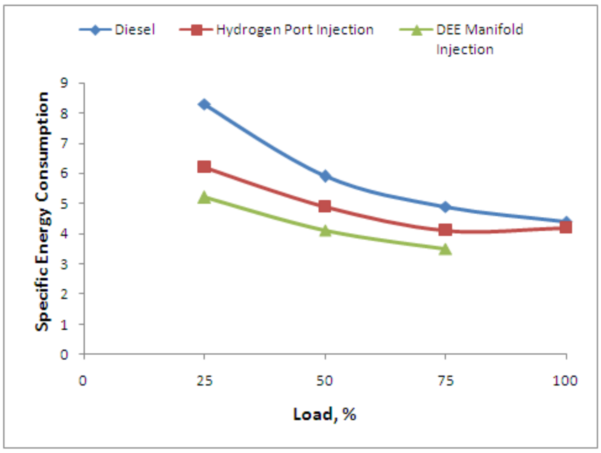

Fig. 3 Effect of Specific Energy Consumption with all Load Conditions

ISBN: 978-988-14048-4-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

C. Oxides of Nitrogen

Figure 4 portrays the variation of NO_X emission with load. The NO_X emission is found to be very less in DEE operated engine. The lowest NO_X of 0.02 g/kWh is observed in DEE operation at 25 % load compared to 25.64 g/kWh in diesel and 20.38 g/kWh in hydrogen port injection with optimum flow of 7.5 lpm of hydrogen. At 75 % load the NO_X emission is found to be 1.28 g/kWh in DEE, 16.13 g/kWh in diesel, 15.92 g/kWh in hydrogen port injection. The reduction in NO_X emission in DEE operation is due to the lower peak combustion temperature as a result of inlet charge cooling.

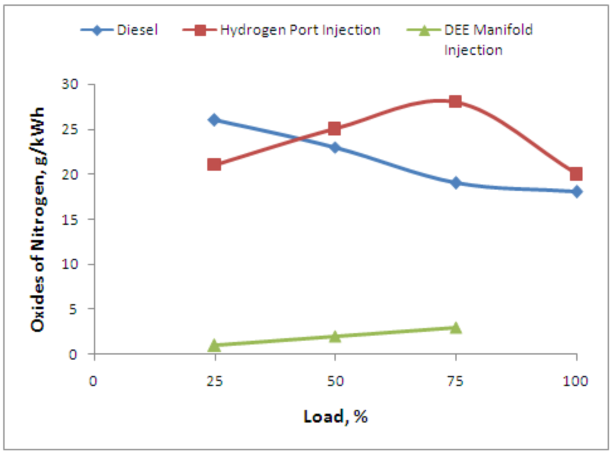

Fig. 4 Effect of Oxides of Nitrogen with all Load Conditions

D. Smoke

The variation of smoke emissions with load is shown in Figure 5. Smoke of 0.2 BSN is observed in hydrogen-DEE operated engine at 25 % load compared to diesel smoke of 1.1 and in the hydrogen diesel dual fuel engine the smoke is observed to be 0.2 BSN. At 75 % load smoke of 0.7 BSN is observed in hydrogen-DEE operated engine compared to diesel smoke of 2.2 BSN and 0.8 BSN for hydrogen operated dual fuel engine can be noticed. A significant reduction in smoke emissions is observed in DEE operated engine is noticed. The reduction in smoke is due to lower carbon/hydrogen ratio of DEE and also due to the absence of carbon in hydrogen. The hydrogen and DEE are available as a homogeneous mixture in the combustion chamber, which also results in the reduction of smoke. There is an absolutely free from liquid fraction of fuel pockets unlike heterogeneous combustion that takes place in a conventional direct injection diesel engine, resulting in a reduction in smoke.

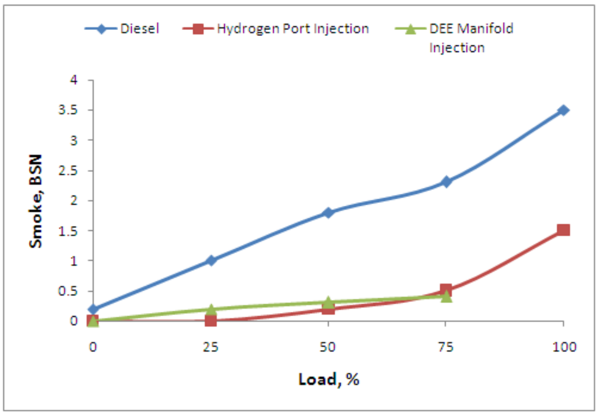

Fig. 5 Effect of Smoke with all Load Conditions

E. Carbon Monoxide

The variation of carbon monoxide with load is depicted in Figure 6. The CO emission is found to be 1.09 g/kWh in DEE operated engine at 25 % load compared to diesel of 0.65 g/kWh while in hydrogen port operated dual fuel engine it is found to be 0.43 g/kWh. At low loads a high concentration of CO emissions is noticed in the case of DEE operation, which is due to lower in-cylinder temperature in addition to the extremely lean mixture available inside the combustion chamber. At 75 % load the DEE operated hydrogen emits CO of 0.15 g/kWh compared to diesel CO of 0.31 g/kWh while the hydrogen operated diesel dual fuel engine emits 0.316 g/kWh. Significant reduction in CO emissions while using DEE at higher power outputs is noticed, since the combustion starts from each ignition center and it is very fast in homogeneous gas air mixture, because of higher concentration of gas that occupies and mixes with air completely in the entire combustion chamber and ignition occurs everywhere in the cylinder simultaneously.

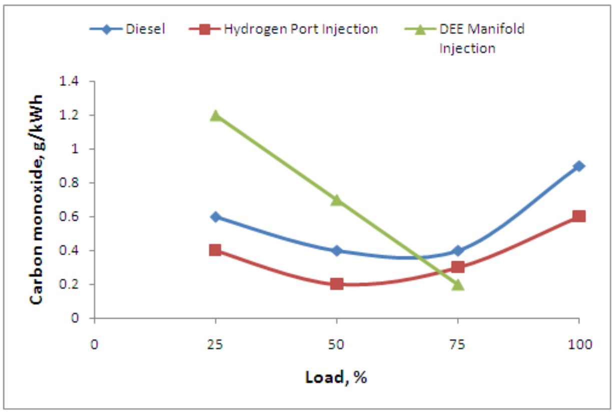

Fig. 6 Effect of Carbon monoxide with all Load Conditions

F. Carbon Dioxide

Figure 7 shows the variation of CO_2 levels for DEE operated engine with load. It can be observed that in DEE operated engines the CO_2 emissions are lesser compared to hydrogen diesel dual fuel engine. DEE shows lesser CO_2 of 0.47 g/kWh at 25 % load compared to diesel of 1.31 g/kWh while for hydrogen-diesel dual fuel engine the CO_2 emission is found to be 0.84 g/kWh. At 75 % load in DEE operated engine the CO_2 is observed to be 0.33 g/kWh compared to diesel CO_2 of 0.78 g/kWh while in hydrogen dual fuel engine it is 0.64 g/kWh. The reduction in CO_2 emission in DEE operated engine is due to lower hydrogen/carbon ratio of DEE resulting in the reduction of CO_2 emissions.

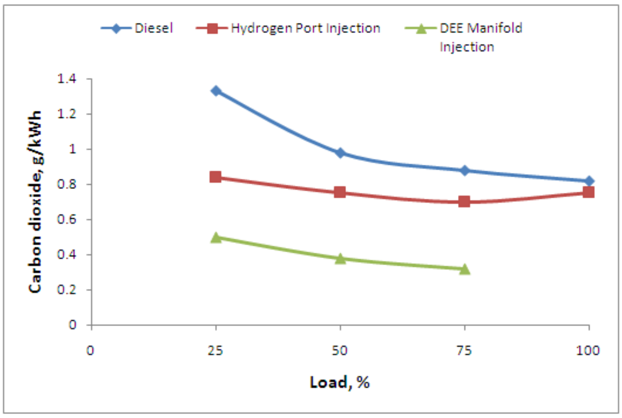

Fig. 7 Effect of Carbon dioxide with all Load Conditions

G. Hydrocarbon

The hydrocarbon variation with load is shown in Figure 8. The HC is found to increase several fold in DEE operated engine compared to that of dual fuel operation of hydrogen. At 25 % load the maximum HC of 2.01 g/kWh is observed in DEE operated engine compared to diesel of 0.27 g/kWh and 0.29 g/kWh in hydrogen port injection with 7.5 lpm of hydrogen flow. The cylinder charge temperature at no load is lesser which leads to flame quenching as the combustion temperature drops significantly resulting in an increase in HC emissions at low load. At 75 % load the HC emission is found to be 0.31 g/kWh in DEE operated engine compared to diesel of 0.13 g/kWh while in hydrogen operated dual fuel diesel engine the HC emission is 0.15 g/kWh. At higher power outputs increasing the quantity of hydrogen fuel results in higher concentration of air-fuel mixture in the combustion chamber. In addition at higher loads the ignition starts at all the points where DEE is present resulting in an increase in charge temperature, hence HC emission reduce compared to that at part load operation.

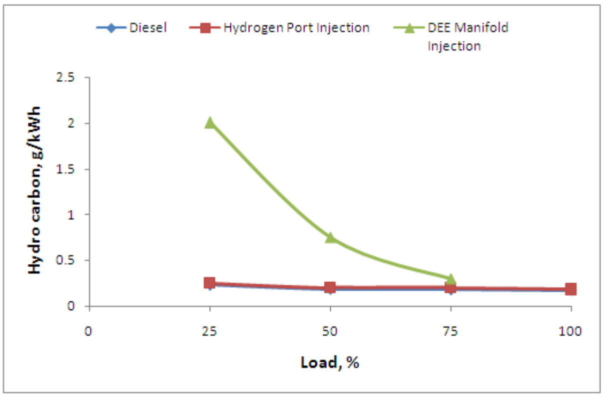

Fig. 8 Effect of Hydro carbon with all Load Conditions

H. Pressure Crank Angle Diagram

Figure 9 portrays the measured pressure data for port injected hydrogen engine, DEE operated engine at 75 % load. The peak pressure in port injected hydrogen engine using diesel as ignition source is found to be 57 bar compared to DEE operation of 46 bar at 75 % load. The peak pressure for baseline diesel is 51 bar. The peak pressure in DEE operated engine reduces significantly due to higher latent heat of vaporization of DEE at inlet manifold that cools the inlet charge to almost 10-15 °C, which in turn reduces the overall charge temperature.

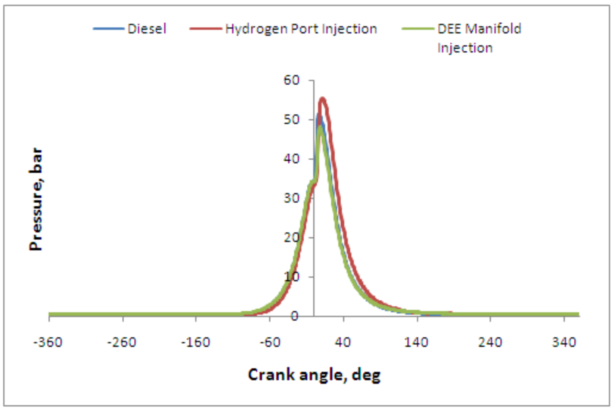

Fig. 9 Effect of Pressure with crank angle

ISBN: 978-988-14048-4-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

I. Heat Release Rate

Figure 10 presents the heat release rate at 75 % load. The peak heat release rate is found to be 87 J/° CA in hydrogen port injected dual fuel engine compared to 59 J/° CA in hydrogen-DEE engine. A reduction in peak heat release rate for DEE is noticed compared to hydrogen diesel dual fuel engine, because of very low inlet charge temperature. The ignition delay generally increases with lower inlet temperature but with DEE due to lower inlet charge temperature the delay period increases but it is compensated by low self-ignition temperature of DEE (433 K), hence there is no change in delay period in DEE operated engine.

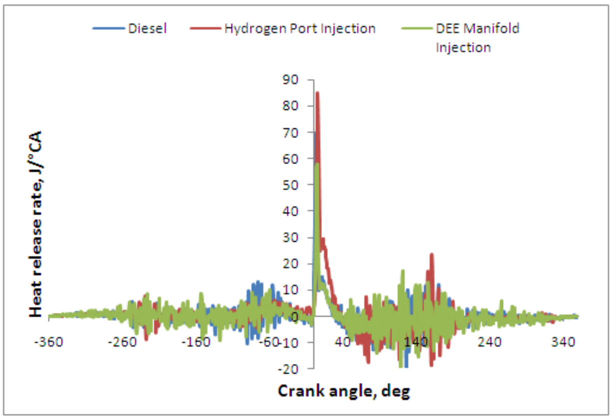

Fig. 10 Variation of Heat release rate with crank angle

V. CONCLUSION

Hydrogen-DEE operated engine is able to run up to 75 % of full load. At full load the engine is not able to attain the rated speed due to severe knocking. The brake thermal efficiency of hydrogen-DEE operated engine increases by 36 % compared to 22 % in port injection. Oxides of nitrogen reduce significantly due to lower combustion temperature in hydrogen-DEE operation. The reduction in NO_X at 75 % load is 14 times for DEE operations. Reduction in smoke by 3 times in both port injection and hydrogen-DEE operation at 75 % load is observed. For hydrogen-DEE operation at 75 % load CO emission decreases by 100 %. CO_2 decreases by 100 % for hydrogen-DEE operation and decreases by 17 % for port injection at 75 % load. 2.5 times increase in HC is observed for DEE operated engine 75 % load. The delay period is found to be 11° CA for diesel and in hydrogen port injection and for DEE it is 9° CA. Using DEE as an ignition source the brake thermal efficiency increases significantly. The emissions such as NO_X, smoke, CO and CO_2 reduce significantly. But HC emission increases significantly with DEE. The problem with DEE operation is correct metering of fuel and proper injection of fuel at optimized timing. Upto 75 % load, port injection DEE operated engine shows improvement in performance with significant reduction in smoke and NO_X emissions. The problem with full load operation can be resolved by adopting hydrogen in-cylinder injection.

ACKNOWLEDGEMENT

The authors sincerely acknowledge “The All India Council for Technical Education” (AICTE), New Delhi, India for the financial support in carrying out this research work.

REFERENCES

[1] David B. Kittelson, Wei Fang, Bin Huang, David B. Kittelson, Dual-Fuel diesel engine combustion with hydrogen, gasoline, and ethanol as fumigants: effect of diesel injection timing, J Eng Gas Turb Pow, 2012;136:081502-1.

[2] M. Shahid, Noriah Bidin, Yacoob Mat, M. Inayat ullah, Production and enhancement of hydrogen from Water: A review, J Ener Res Tech, 2012;134:034002-1.

[3] Rahul Banerjee, Probir Kumar Bose, An Experimental Investigation on the Role of Hydrogen in the Emission Reduction and Performance Trade-Off Studies in an Existing Diesel Engine Operating in Dual Fuel Mode Under Exhaust Gas Recirculation, , J Ener Res Tech, 2012;134:012601-1.

[4] N. Saravanan, G. Nagarajan, C. Dhanasekaran, K.M. Kalaiselvan, Experimental investigation of hydrogen port fuel injection in DI diesel engine, Int. J Hyd Ener, 2007;32:4071-4080

[5] M. Masood, S. N. Mehdi, P. Ram Reddy, Experimental investigations on a hydrogen-diesel dual fuel engine at different compression ratios, J Eng Gas Turb Pow, 2007;129: 572.

[6] L.M.Das, Near – term introduction of hydrogen engines for automotive and agricultural application, Int J Hyd Ener, 2002;27:479-487.

[7] Eiji Tomita, Nobuyuki Kawahara, Zhenyu Piao, and Shogo Fujita, Hydrogen Combustion and Exhaust Emissions Ignited with Diesel oil in a Dual Fuel Engine, J Fuels and Lubr, 2001;01:3503.

[8] S.Verhelst and R. Sierens, Aspects Concerning the Optimization of a hydrogen fueled engine, Int J Hyd Ener, 2001;26:981-985.

[9] J.D. Naber and D.L.Siebers, Hydrogen combustion under diesel engine conditions, Int J Hyd Ener, 1998;23:363-371.

[10] H.S. Yi, S.J. Lee and E.S. Kim, Performance evaluation and emission characteristics of in-cylinder injection type hydrogen fuelled engine, Int J Hyd Ener, 1996;21:617-624.

[11] S.J.Lee. H.S.Yi and E.S.Kim, Combustion characteristics of intake port Injection type hydrogen fuelled engine, Int J of Hyd Ener, 1995;20:317-322.

[12] L.M.Das, Fuel induction techniques for hydrogen operated engine, Int J Hyd Ener, 1990;15:833-842.

[13] B. Haragopala Rao, K.N. Shrivastava and H.N. Bhakta, Hydrogen for dual fuel engine operation, Int J Hyd Ener, 1983;8:381-384.